U.S. Department of Energy's Office of Science

Office of Fusion Energy Sciences

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General Plasma Science Program

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Recommendations of the 1995 National Research Council Report

"Plasma Science"

- Reinvigorate basic plasma science with emphasis on university-scale research

- The DOE and NSF should provide increased support for basic plasma science

- Agencies supporting plasma science should cooperate and coordinate plasma science funding

Recommendations of the 2001 National Research Council Report

"An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program"

- A systematic effort to reduce the scientific isolation of the fusion research community from the rest of the scientific community is urgently needed

- Several new centers, selected through a competitive, peer-review process and devoted to exploring the frontiers of fusion science, are needed for both scientific and institutional reasons

General Plasma Science (GPS) Program

The General Plasma Science program can be divided into 5 elements:

1. The NSF/DOE Partnership in Basic Plasma Science and Engineering,
   Basic Plasma Science Facility (LAPD) at UCLA funded by NSF/DOE.

2. General Plasma Science program supported at the DOE Laboratories

3. Plasma Physics Junior Faculty Development Program

4. The Fusion Science Centers
   Two Fusion Science Centers were funded

5. The Atomic Physics program.

The experimental parts of the program are carried out at the NIST and ORNL.

Center for Magnetic Self-Organization (CMSO) in Laboratory and Astrophysical Plasma

Physics Frontier Center is funded by NSF with DOE funding for PPPL & LLNL.

Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas (CMSO)

Purpose: to solve key plasma physics problems common to the lab and astrophysics

Method: unite laboratory (fusion) plasma physicists and astrophysicists in collaboration (including experiment, theory, computation)

Participants: 40 co-investigators, 15 postdocs, 15 grad students (evenly spread over lab and astro)

8 Institutions: Wisconsin, Princeton, U. Chicago, U. New Hampshire, LANL, Swarthmore College, SAIC, LLNL

Experiments: MST, MRX, SSX, RWM expt, RSX, SSPX, liquid metal expts (MRI, Madison dynamo)

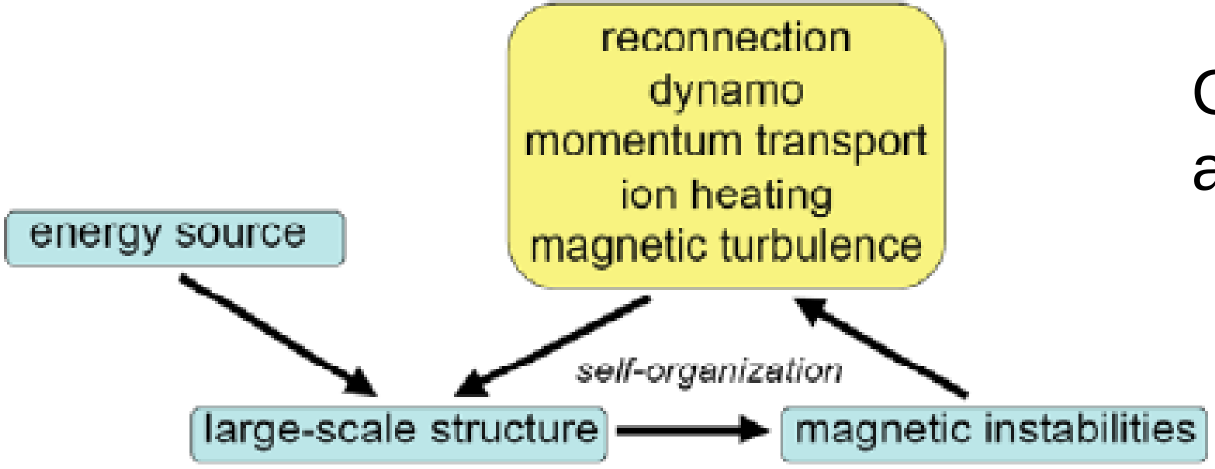
Overaching questions

- *Why is the universe magnetized?*

find steady, impulsive or turbulent fields at all scales (solar to extra-galactic), with some characteristics as in lab experiments.

- *How do magnetic fields affect the structure of plasmas*

field dynamics rearranges macroscopic quantities, such as the magnetic field, plasma flow, thermal energy (in astro and lab)



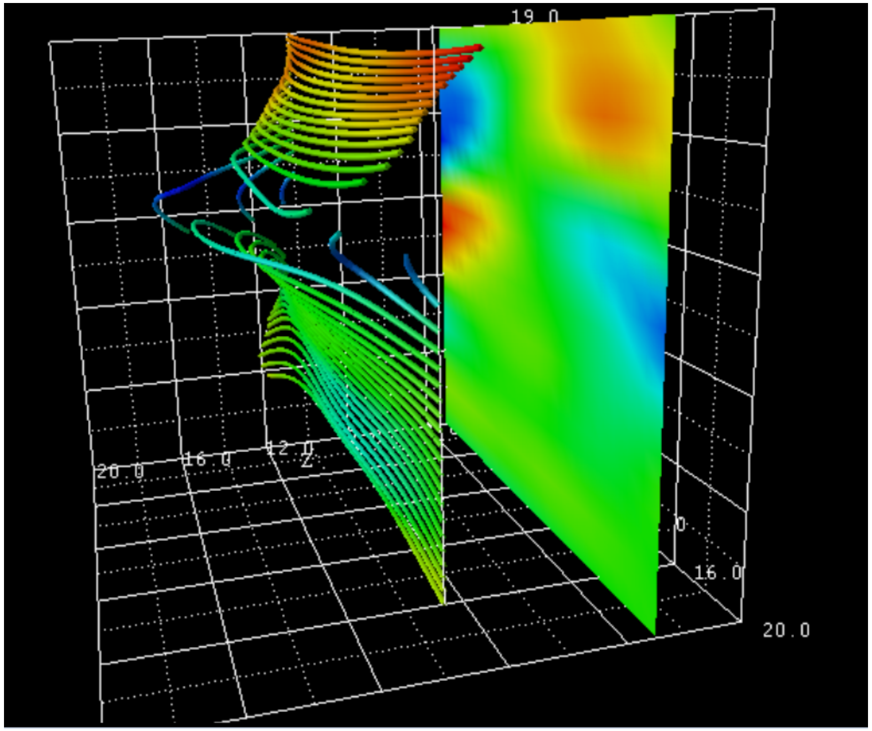
CMSO organized around these 5 topics

Sample highlights

Reconnection

two-fluid effects verified experimentally (MRX, SSX, MST),
key to enhanced reconnection rate in astro and lab,
predicted by theory community, now established in experiment

Quadrupole field from Hall effect in MRX

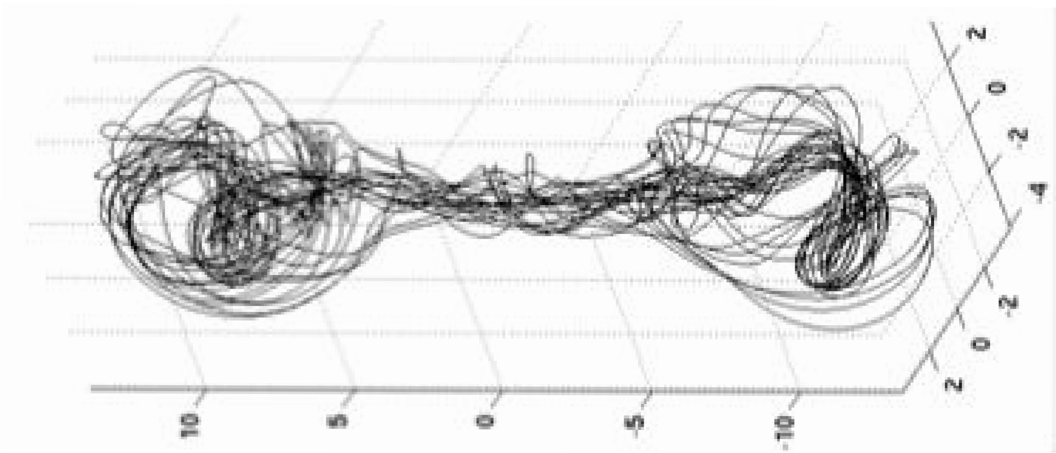


Similar to observations of reconnection in magnetosphere

Dynamo

- *Magnetic field important in jet/lobe dynamics*

Shown computationally by LANL astrophysicist, motivated by RFP and spheromak experiments



B lines from MHD computation,

Modeling astrophysical jet and lobes, extragalactic)

Jet stability, lobe formation, flux conversion have physics links to lab plasmas

Momentum transport

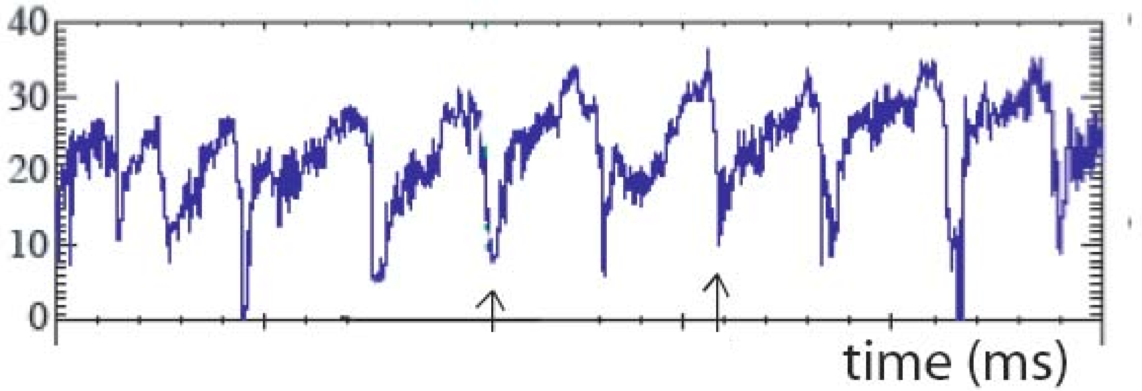
• Current-driven instability produces momentum transport

• shown in MST - momentum transport from tearing instability (reconnection)

• occurs at sawtooth crashes

toroidal flow

(km/s)



This mechanism is now being studied for astrophysical disks and jets (by CMSO fusion theorists, guided by CMSO astrophysicists)

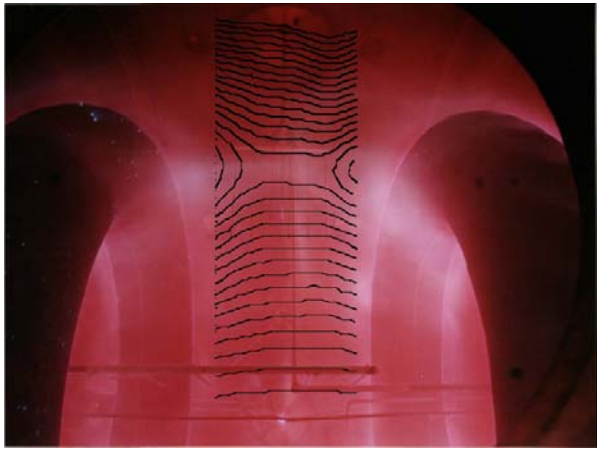
A complement to the well-studied flow-driven magnetorotational instability

Magnetic Reconnection Experiment (MRX)

M. Yamada, H. Ji, S. Gerhardt

- **To study fundamental physics of fast reconnection commonly observed in fusion, space, and astrophysical plasmas.**
  - **Why reconnection is fast?**
  - **How magnetic energy is dissipated to plasma thermal and kinetic energies?**

Solar flares



MRX

Aurora

Recent Highlights from MRX Research

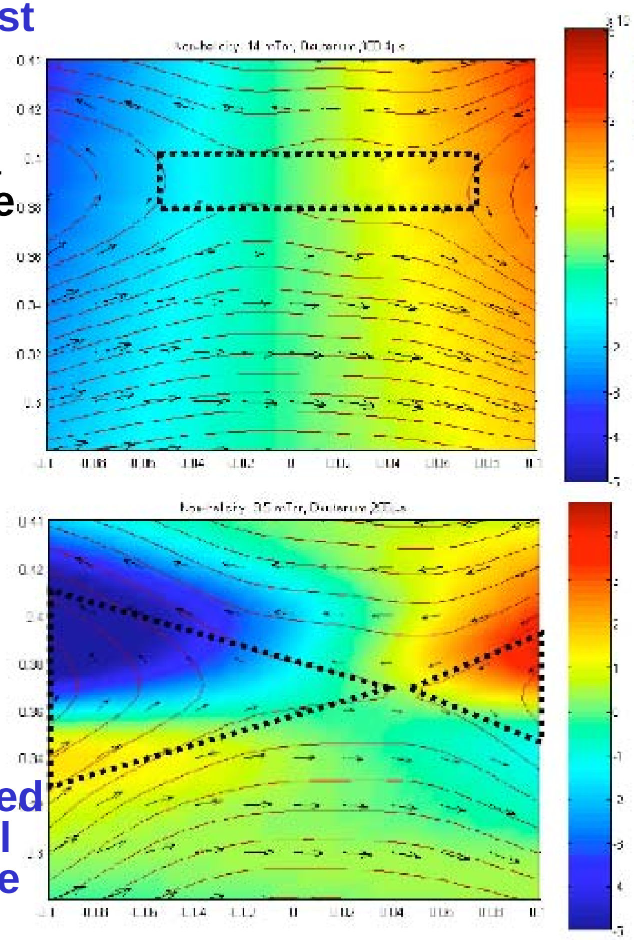
- **Identified possible causes of fast reconnection**

  Hall effects observed through a quadrupole field account for the high resistivity observed in the low collisionality regime

  First observation of electron diffusion layer

  Magnetic LHDW fluctuations correlate well with resistivity enhancement

- **An experimental scaling obtained in the transition from collisional to collision-less regime (Change of the neutral sheet profile)**



Neutral sheet Shape in MRX

Changes from "Rectangular S-P" type to "Double edge X" shape as collisionality is reduced

Rectangular shape

Collisional regime: $\lambda_{mfp} < \delta$

Slow reconnection

No Q-P field

X-type shape

Collisionless regime: $\lambda_{mfp} > \delta$

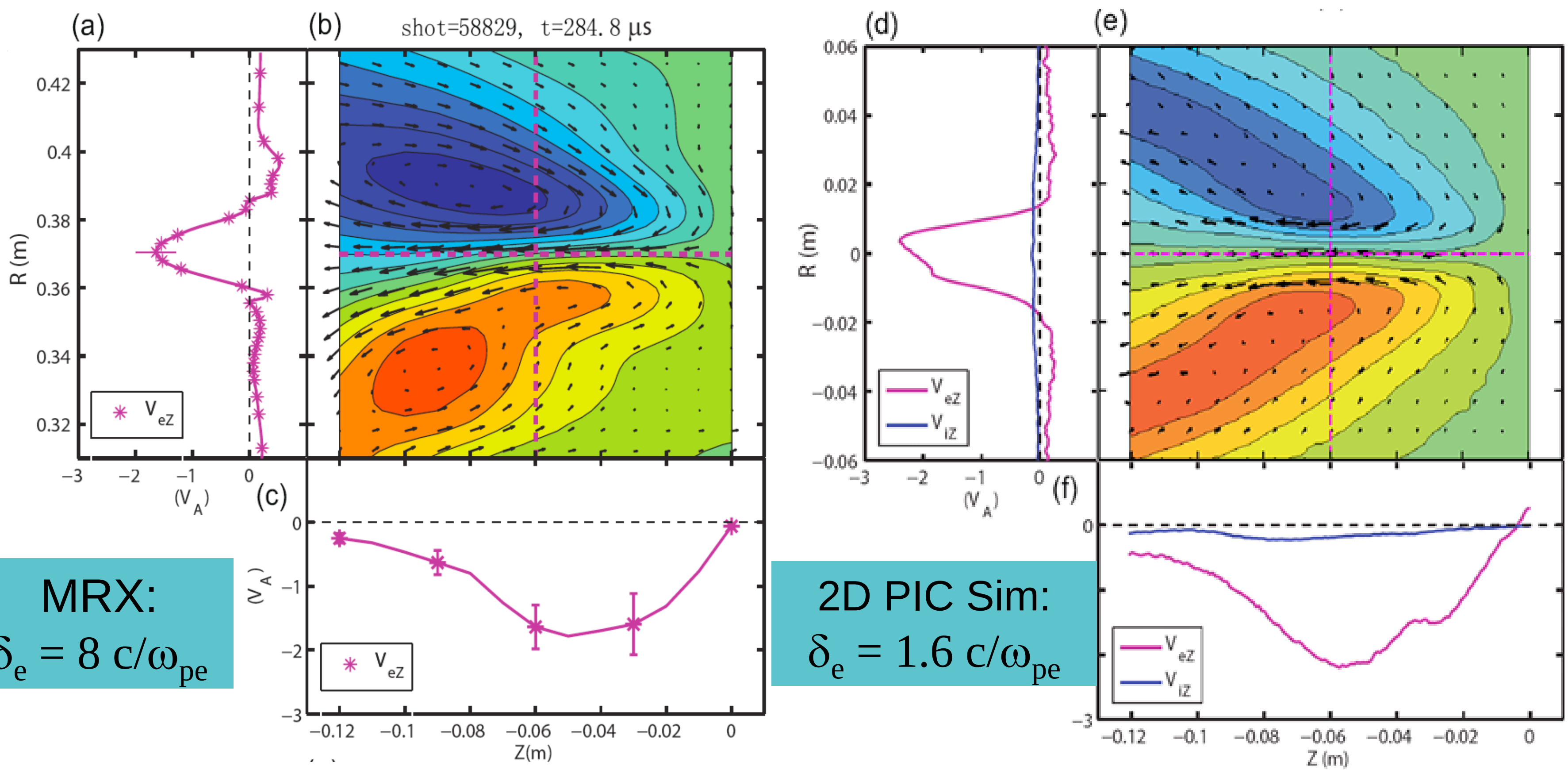
Fast reconnection

Q-P field present

Cited in NRC 2010 Report
Yamada et al, PoP, 2006

Ren et al. PRL (2005); Yamada et al. PoP (2006)

First Detection of Electron Diffusion Layer Made in MRX: Comparison with 2D PIC Simulations



MRX:
$\delta_e = 8\ c/\omega_{pe}$

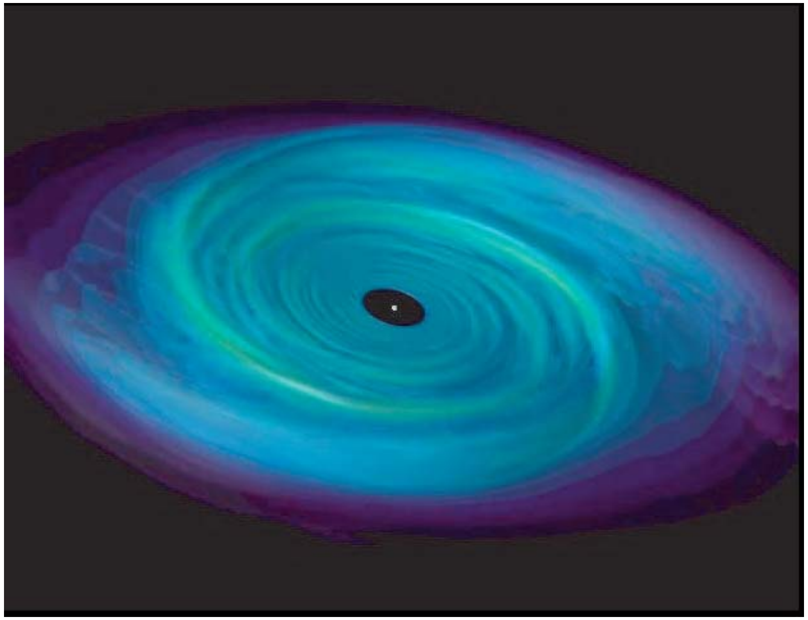
2D PIC Sim:
$\delta_e = 1.6\ c/\omega_{pe}$

All ion-scale features reproduced; but electron-layer is 5 times thicker in MRX $\Rightarrow$ importance of 3D effects

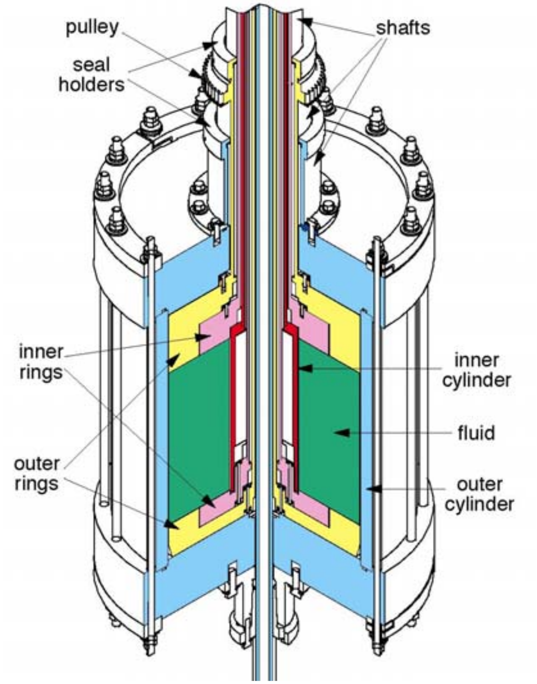
Magnetorotational Instability (MRI) Experiment

H. Ji, M. Nornberg, J. Goodman (astrophysics)

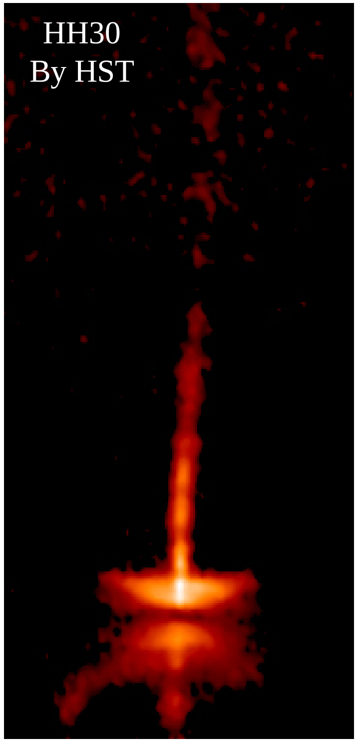
- **To study fundamental physics of fast angular momentum transport in accretion disks**
  - **Can hydrodynamic turbulence support fast accretion?**
  - **How MRI transport angular momentum?**



Accretion Disks



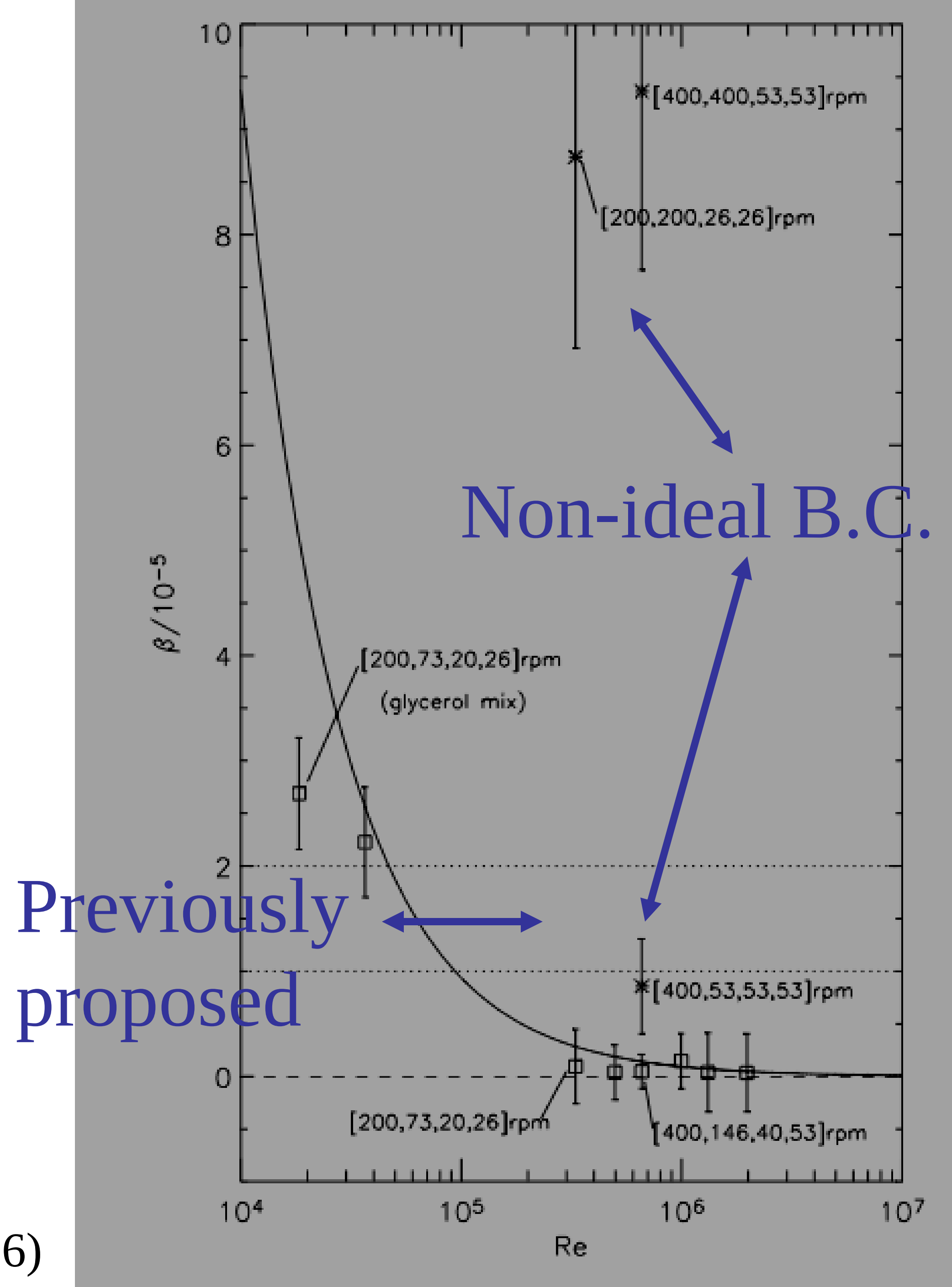
MRI Experiment



Protostellar Disk

No Signs of Turbulence up to Re=2×10^6

- Remarkable from our daily experience
- Direct measurements of Reynolds stress (first this kind)
  - Dual Laser Doppler Velocimetry
- Normalized Reynolds stress: $< 6.2\times10^{-6}$ with 98% confidence, as compared to the required values of $\sim10^3$



Ji et al, Nature 444, 343 (2006)

Highlights of FSC activities in 07-08

FSC

- → **Participating Institutions: UR, MIT, UCSD, OSU, UNR, UT, UCLA, GA, LLNL, ILSA**
- → **OFES Funding: FY08-DOE \$1.094M, FY09-DOE \$1.069M**
- → **2nd FSC Summer School in High Energy Density Physics**
- → **22 refereed papers published or submitted: Science (1); Phys. Rev. Lett. (7); Phys. Plasmas (13); J. Comp. Phys. (1); Rev. Sci. Instrum. (2)**
- → **10 invited talks: APS (6); IFSA (3); Anomalous Absorption (1)**
- → **Main facilities: OMEGA (UR-LLE), TITAN (LLNL), THOR (UT)**
- → **16 faculty and senior scientists involved with the FSC**
- → **13 research associates and post-docs (partially or fully funded by the FSC)**
- → **18 PhD students**

FSC EDUCATION. 2nd FSC summer school in HEDP, UCSD campus, July 29-August 4, 2007

FSC

→**Sponsors:**
- FSC (DOE-OFES)
- ILSA
- IMDEC
- GA

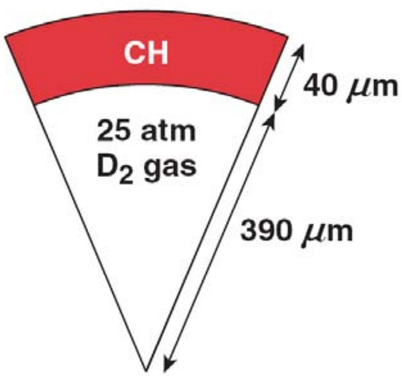
→**50 scholarships to Grad/UnderGrad students**

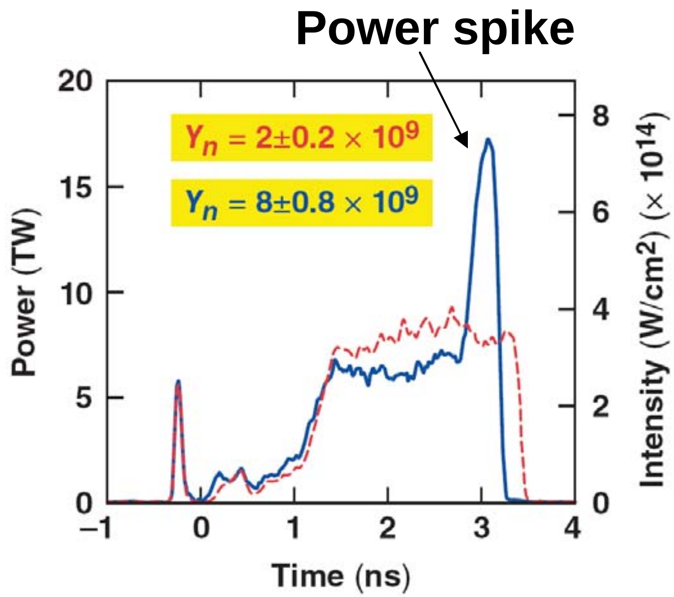
→**100 Students:**
- 69 Graduate Students
- 5 Undergraduates
- 10 Postodcs
- 16 Research Scientists

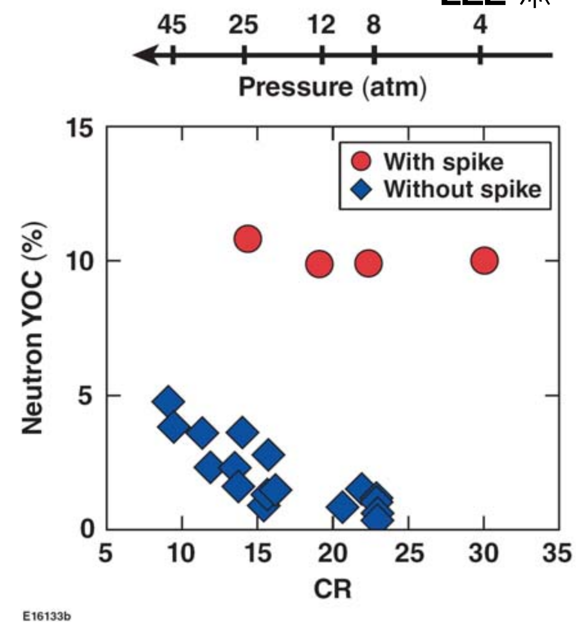
→**14 Lecturers**

Shock Ignition. Experiments on OMEGA confirm higher fusion yields when a shock is launched by a late laser power spike. Highest areal density of 0.3g/cm^2 achieved with late shock.

E_L = 19 kJ, α = 1.3,
V_i = 1.7 × 10^7 cm/s, SSD off







Neutron yield increases considerably for shock-ignition laser pulse shapes

Shock-Ignition shot 48674 achieved an areal density of 0.3g/cm^2. Highest ρR thus far.

The measured-to-calculated neutron-yield ratios are close to 10% for a hot-spot convergence ratio of 30.

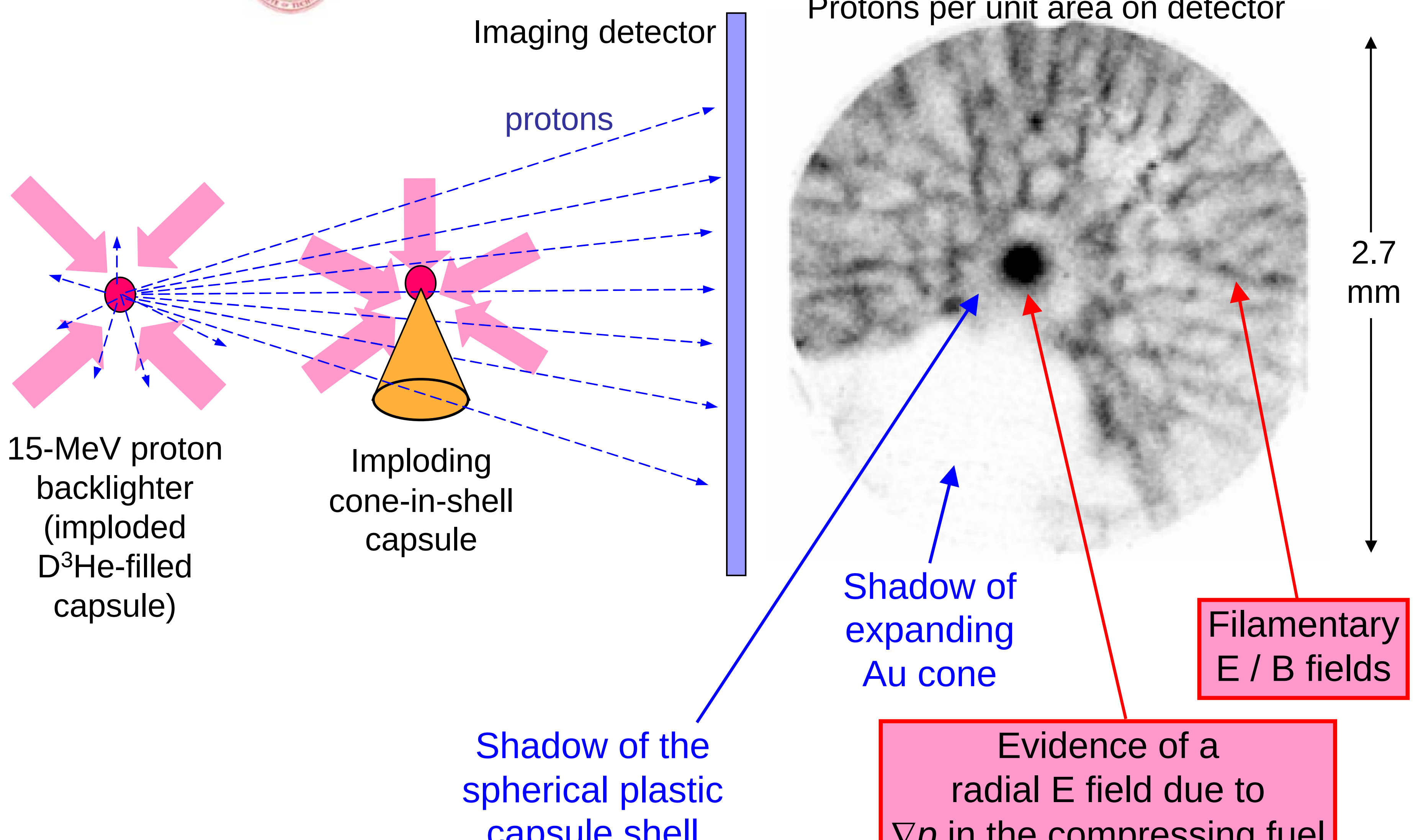
Cryogenic-implosion Shock-Ignition experiments are scheduled for '08-'10

R. Betti, et al, Phys. Rev. Lett. 98, 155001 (2007)
W. Theobald,et al Phys. Plasmas (in press, 2008)

HEDP

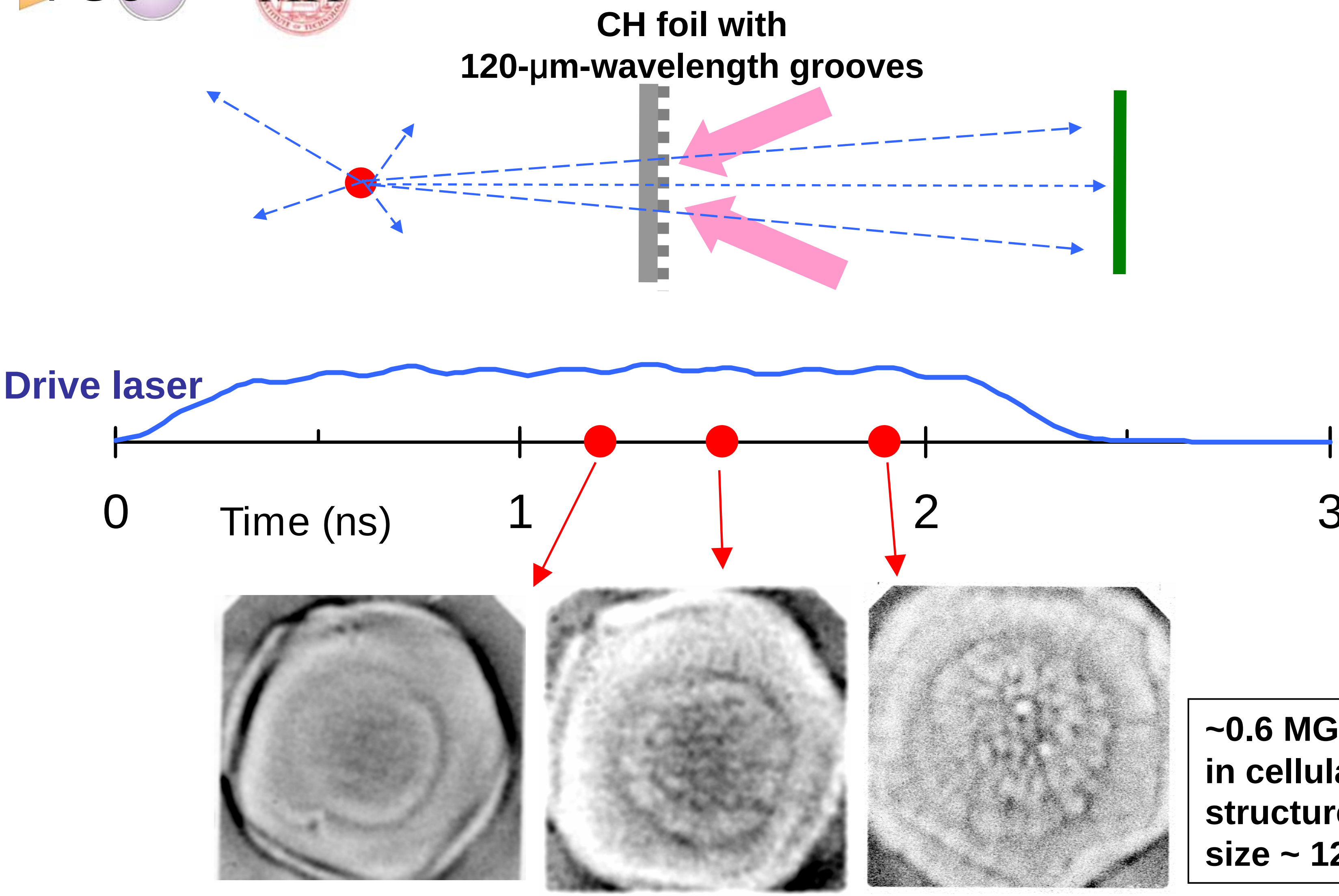
Published in ***Science**** (2-29-2008)

Image of an imploding ICF capsule, showing features never before observed



*J.R. Rygg *et al.*

HEDP: Proton radiography is used to image the evolution of the multimode RT instability and its B-field generation



~0.6 MG fields in cellular structures with size ~ 120 μm

Petrasso *et al*., APS 2007

The Center for Multiscale Plasma Dynamics (CMPD)

CMPD/CMSO Winter School 2008

CMPD Education/Research 2007-08

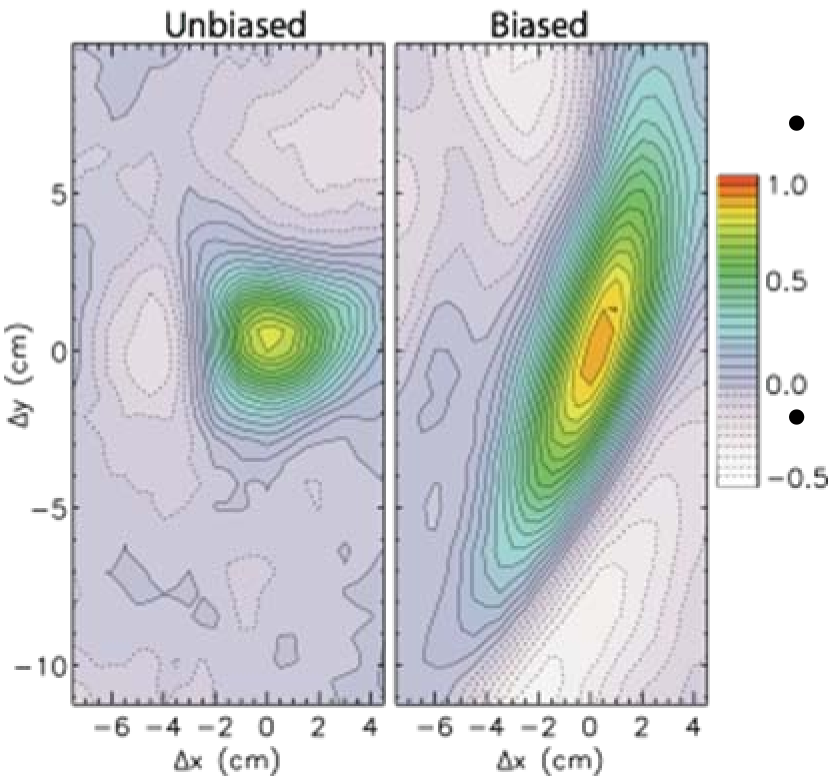
- CMPD Winter School is very visible, very popular. Full schedule, slides:
  http://home.physics.ucla.edu/calendar/conferences/cmpd/
  Co-sponsored with Center for Magnetic Self-Organization
- Winter School 2008 topic:
  Instabilities in Laboratory, Space and Astrophysical Plasmas
- More than 110 senior graduate students and post-docs attended, from US and abroad. General agreement from anonymous student evaluations: This was the best Winter School so far.

In addition to the Winter School:

- CMPD graduate students gave invited talks at APS, Sherwood, and Intl Plasma Simulation conference (Austin).
- CMPD-supported post-docs: IFS (1), U. Del (1), Maryland (2), UCLA (2)
- CMPD-supported junior faculty: Maryland (1.5: Tatsuno, Gumerov)
- Nearly all CMPD funding dedicated to students, post-docs, & Jr faculty.

Example: CMPD supporting experiment-simulation comparisons for improved predictive capability

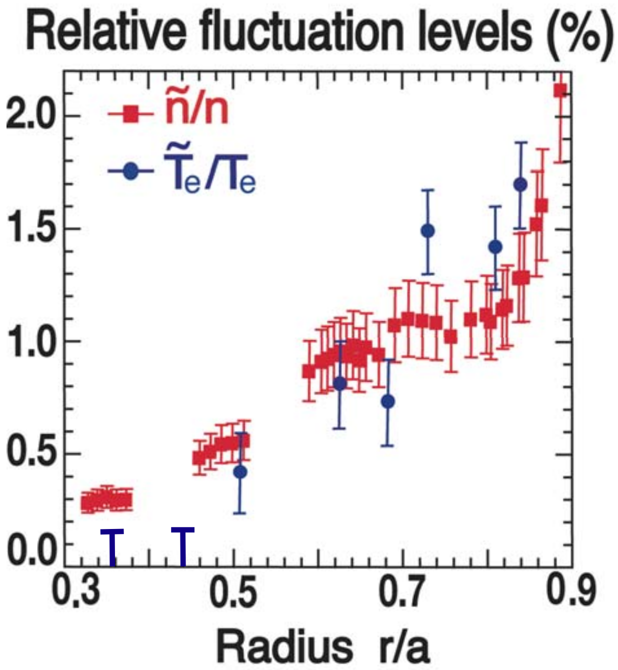
- Ongoing focus of UCLA CMPD activities on experiment-simulation comparison using LAPD and DIII-D



- Measurements of nonlinear Alfvén wave interactions and drift-Alfvén wave turbulence on LAPD
- Right: modifications of turbulent correlation function with applied bias in LAPD, T. Carter, J.E. Maggs (UCLA)

- Comparisons with BOUT underway, successful modification to run LAPD geometry (P. Popovich (UCLA), M. Umansky (LLNL))

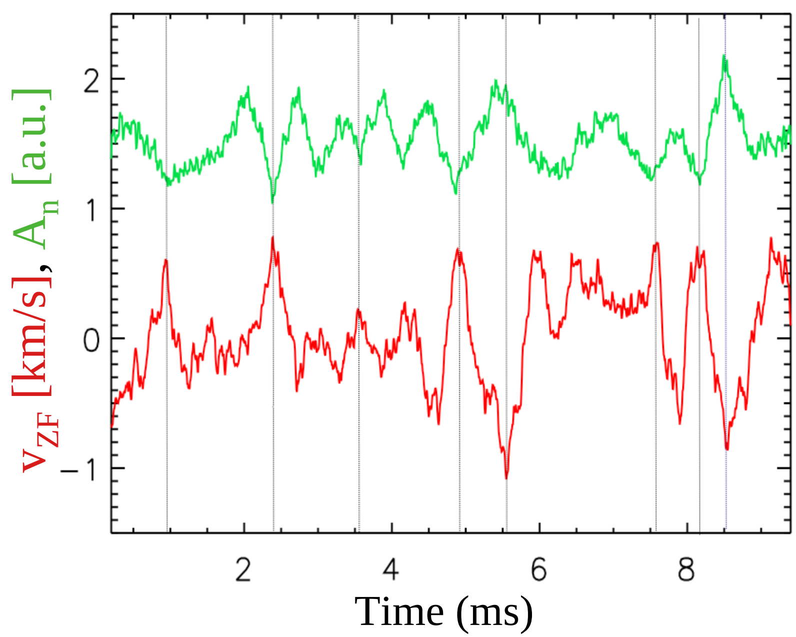
Example: Detailed measurements on DIII-D constrain simulation predictions



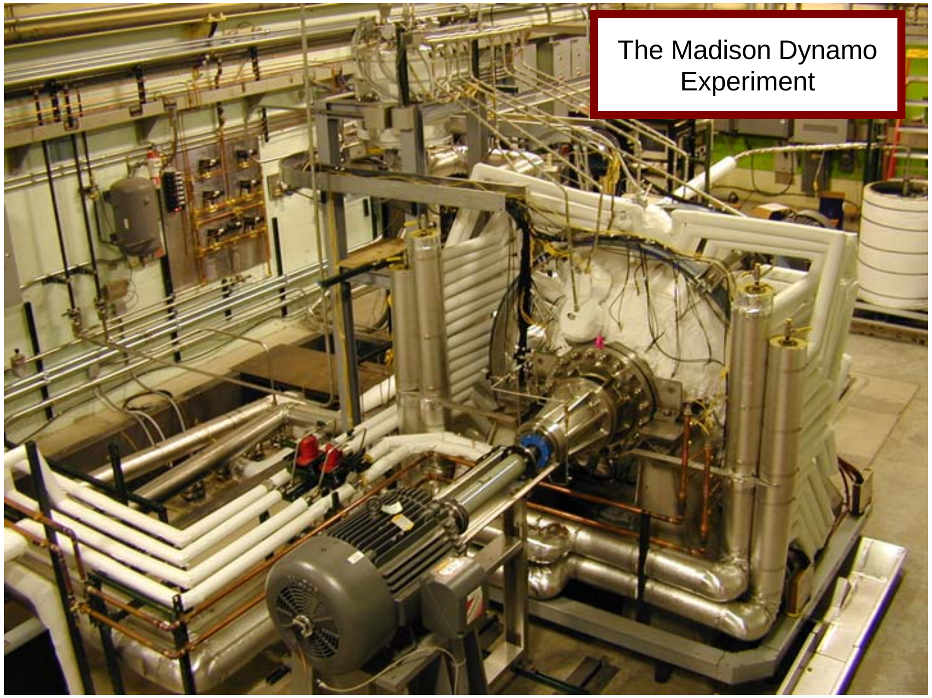
- Measurements of electron temperature (CECE) and density (BES) fluctuation profiles (A.White (UCLA), G. McKee (U. Wisconsin) *et al*)

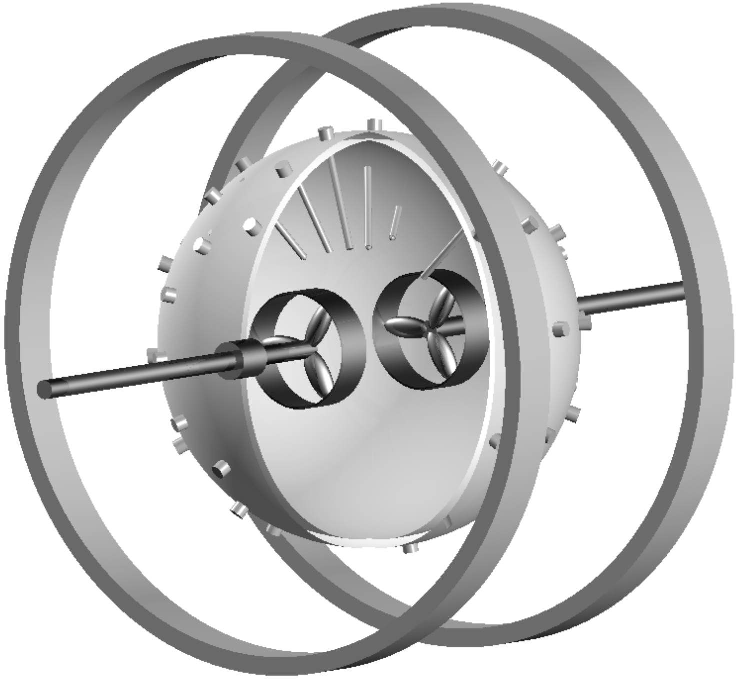
- Detailed comparison to GYRO simulations (C. Holland (UCSD), et al)

- Anti-correlation between zonal flow and density fluctuation amplitudes (Doppler reflectometry), L. Schmitz (UCLA)



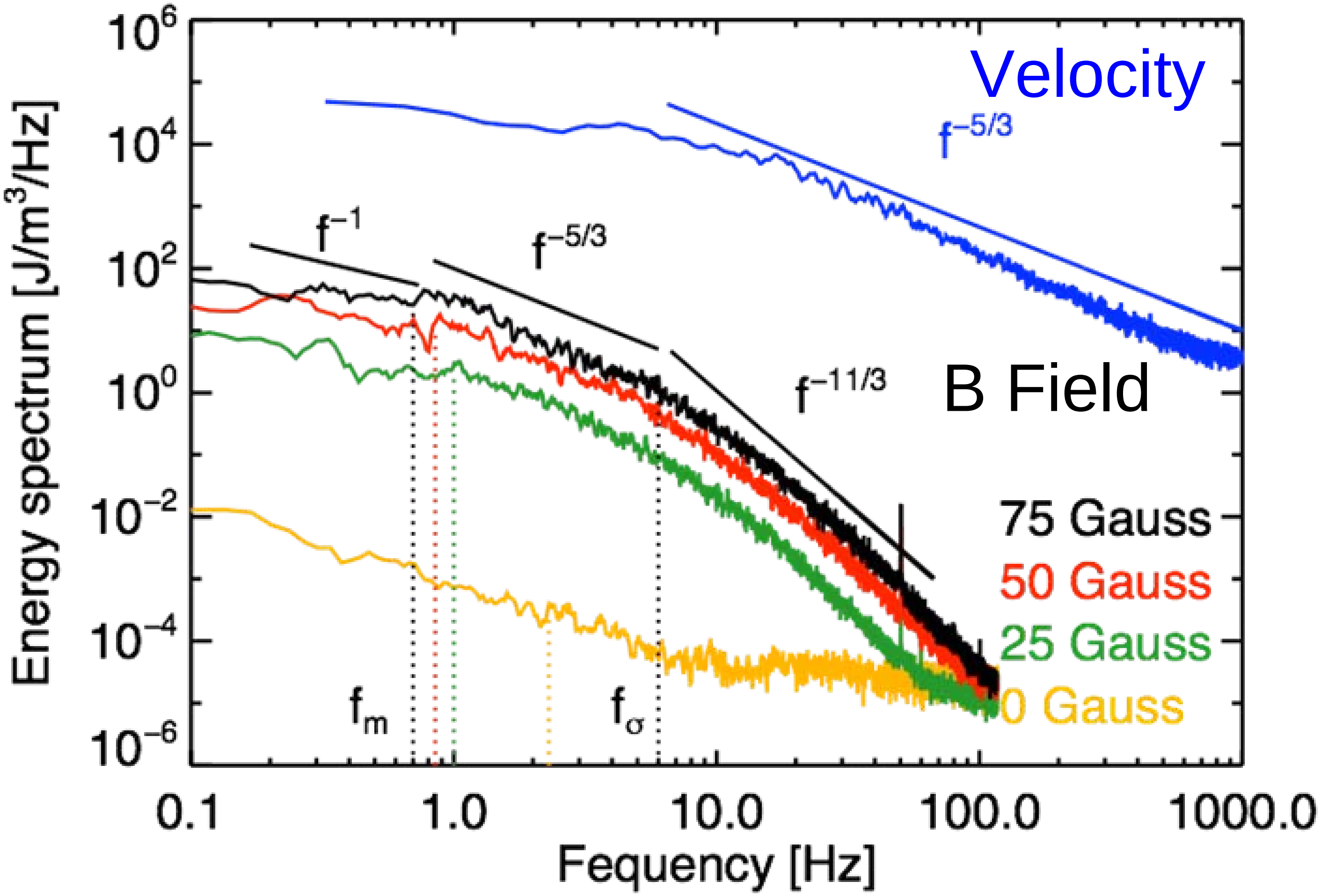
The Madison Dynamo Experiment investigates self-generation of magnetic fields in turbulent flows of liquid metal





- 300 gallons of liquid sodium, 150 kW of mechanical power: $Rm \sim Rm_{crit} \sim 100$
- Power scaling is challenging: $P_{mech} \sim Rm^3 / L$
- $Rm/Re=10^{-5}$ (always turbulent)
- confinement is simple, and conductivity is uniform

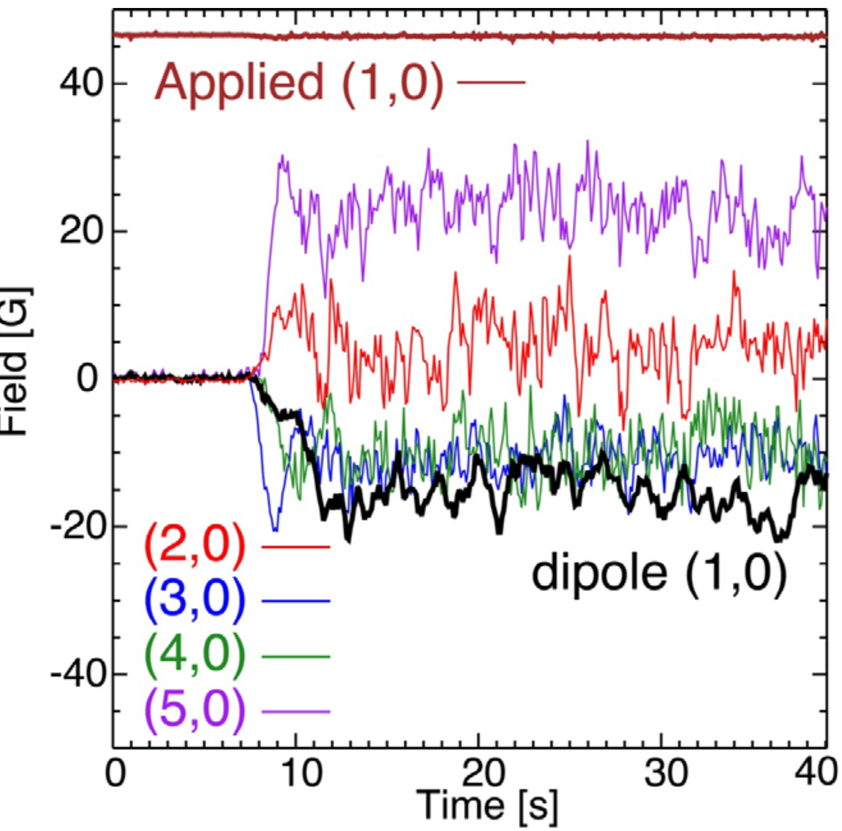
Spectra are turbulent: the magnetic field is passively advected and is much smaller than the kinetic energy

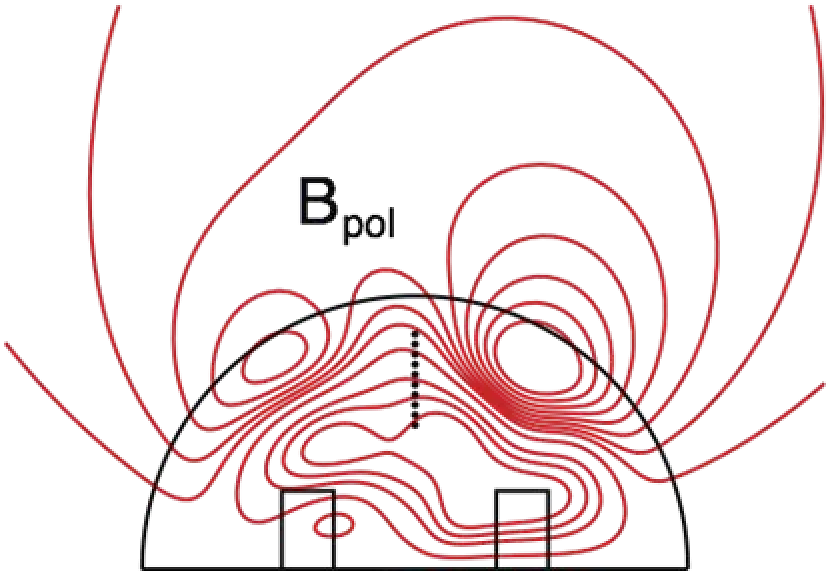


Nornberg, Spence, Bayliss, Kendrick, and Forest, *Measurements of the magnetic field induced by a turbulent flow of liquid metal*, Phys. Plasmas **13** 055901 (2006).

The mean induced magnetic field has a dipole moment

components of Y_{lm}



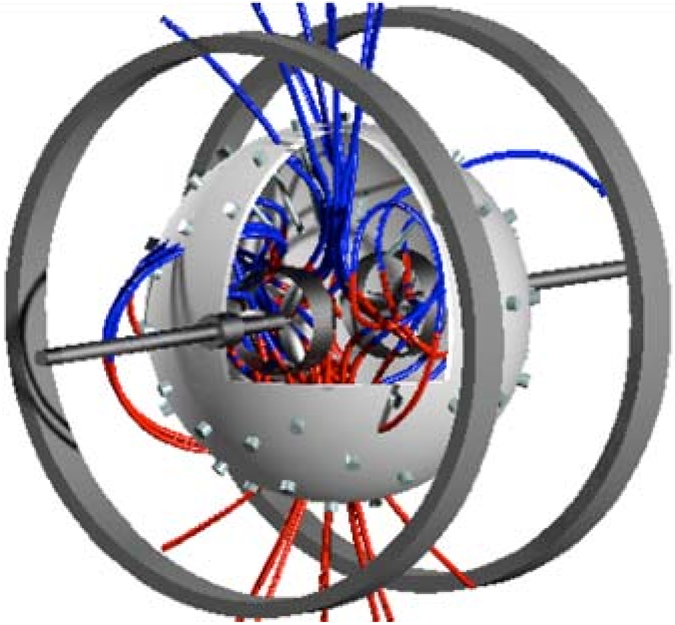


Impossible to reconstruct with axisymmetric flows!

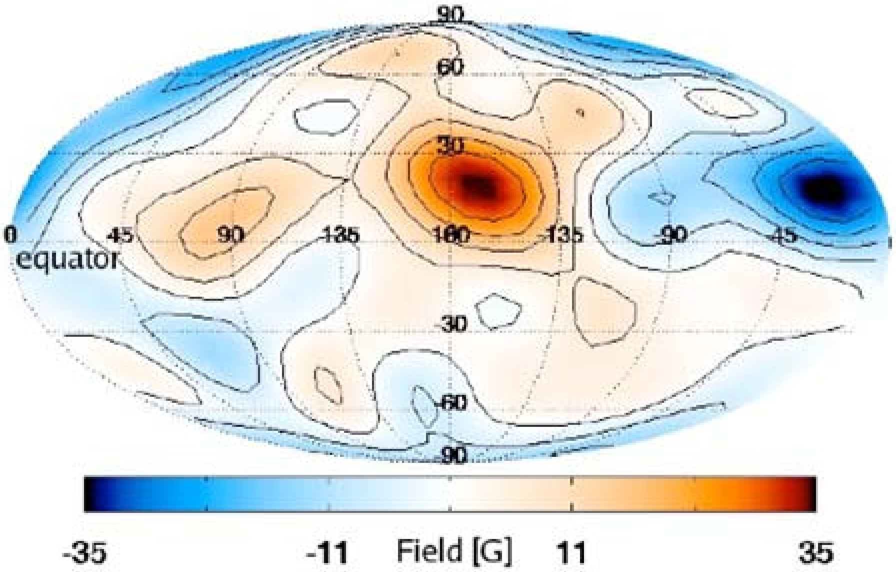
Spence, Nornberg, Jacobson, Kendrick, and Forest, *Observation of a turbulence-induced large-scale magnetic field*, Phys. Rev. Lett. **96** 055002 (2006).

Intermittently excited magnetic eigenmode has structure similar to that predicted for the mean-flow, self-generated dynamo

Predicted



Observed



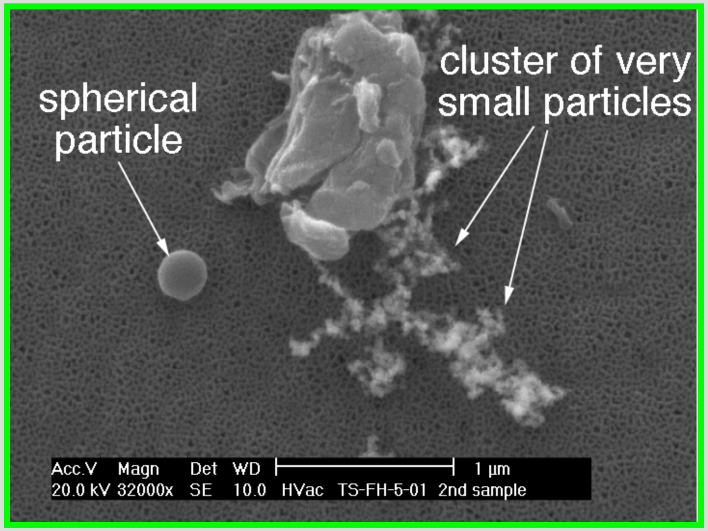
Nornberg, Spence, Jacobson, Kendrick, and Forest, *Intermittent magnetic field excitation by a turbulent flow of liquid sodium,* Phys. Rev. Lett. 97 044503 (2006).

Dusty Plasma

"Dust" = small particles of solid matter, 10 nm – 1 mm, usually dielectric

Astronomy: star-forming regions

Credit: NASA, HST, J. Hester & P. Scowen



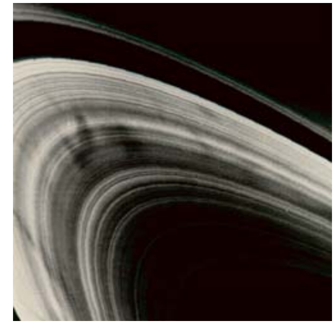
Fusion: dust from Tore Supra tokamak

Credit: Phil Sharpe
Idaho National Laboratory

Who cares about dusty plasmas?

Solar system

- Rings of Saturn
- Comet tails
- Planetary formation

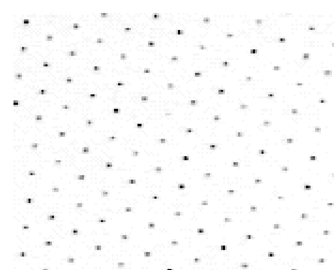


Manufacturing

- Particle contamination
  (Si wafer processing)
- Nanomaterial synthesis

Basic physics

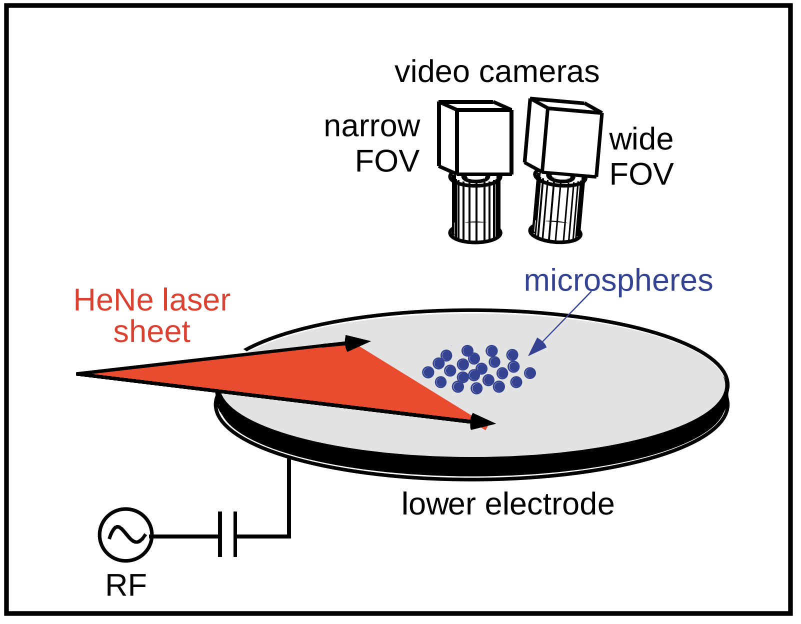
- Waves
- Transport coefficients
- Condensed matter physics

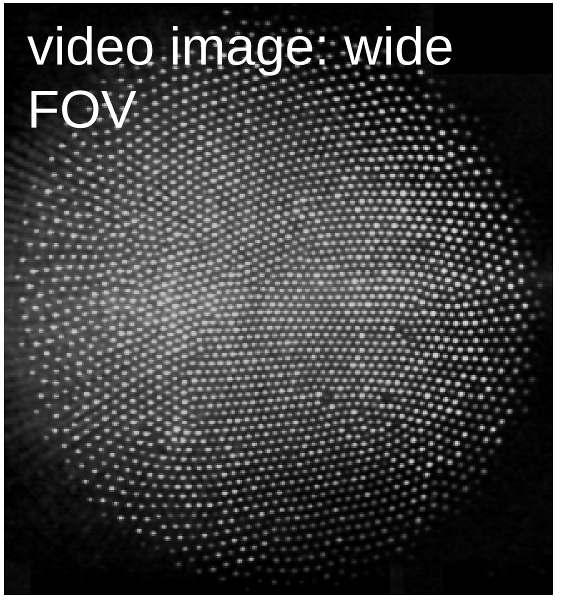


Fusion

- Tritium inventory

Experiment setup





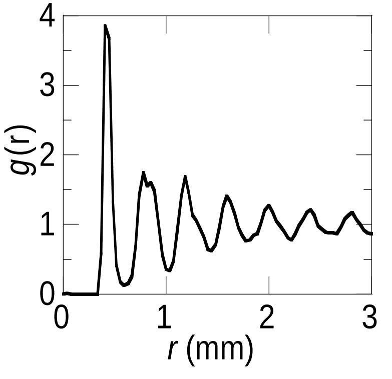
Levitation and confinement of dust

- Charged dust particles sediment to bottom of plasma, are levitated by sheath E field
- Infinite confinement time due to ambipolar E fields

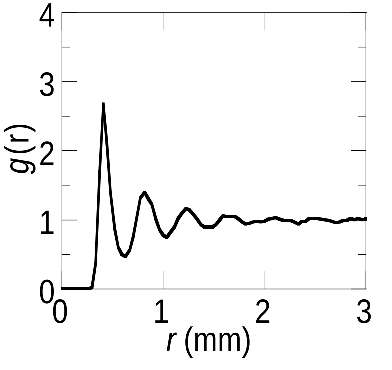
Monolayer suspension:

- Finite-size large cluster
- Crystalline, unless an effort is made to melt it by adding random energy

Pair correlation function

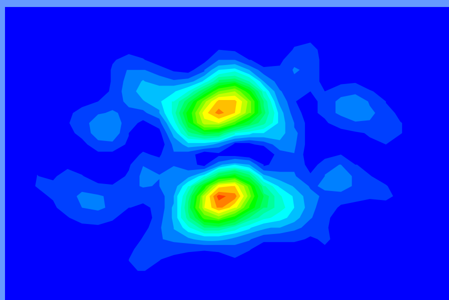


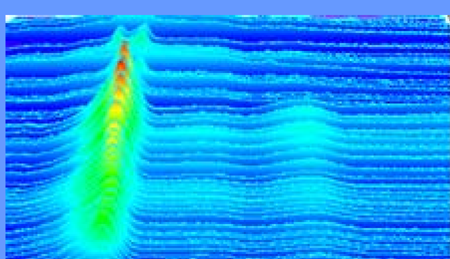
Crystal



Liquid

The ORNL Atomic Physics for Fusion Program





<u>Mission:</u> Produce, collect, evaluate, and disseminate atomic, molecular, and particle-surface interaction (AM&PSI) data needed by the fusion and plasma science community

- Wide scope of AM&PSI data required for plasma diagnostics, modeling, technology development

- Utilize and extend techniques for production of new AM&PSI data and basic understanding

- Close connection to both atomic physics and plasma science communities in order to collect relevant data and provide results needed in fusion and other plasma applications

- Accomplish mission through three synergistic program elements – The Controlled Fusion Atomic Data Center, the Multicharged Ion Research Facility, and Atomic Theory